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Theoretical and experimental bioeffects research for high-power terahertz electromagnetic energy

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ABSTRACT

Historically, safety analyses for radio frequency emission and optical laser exposures have been designed to define the threshold level for tissue damage. To date, no experimental studies have documented damage thresholds to living tissues in the terahertz (THz) range of electromagnetic frequencies (0.1 – 10 THz). Exposure limits exist as extrapolated estimates at the extreme bounds of current occupational safety standards for lasers and radio frequency sources. Therefore, due to the lack of published data on the safety of terahertz emissions, an understanding of the bioeffects of tissue exposures to terahertz beams is necessary. The terahertz frequency band represents an intermediate range in which both optical and radiofrequency methods of theory and experimentation can be selectively employed and compared for consistency. We report on work recently completed to reconcile the theoretical methods of optical and radio-frequency radiative transport modeling, while additionally discussing preliminary theoretical estimates of damage thresholds to skin tissue from terahertz energy and work planned to validate these findings experimentally.

Keywords: Terahertz, damage thresholds, safety standards, bioeffects

1. INTRODUCTION

Technology in the terahertz range of the electromagnetic spectrum (0.1 THz to 30 THz) is rapidly advancing. Unlike the past, high powered sources are now available. There are many valuable uses for such sources including medical imaging and security applications. The unique absorption spectra of biological, chemical and explosive materials within the terahertz spectrum make terahertz spectroscopy particularly useful for the latter. This unique absorption can potentially be combined with imaging for standoff detection of such materials. Spectroscopic databases of materials are currently being compiled.

Before any systems can be utilized, however, the safety of the terahertz emissions must first be evaluated. This must be done to protect those who would be exposed as well as to avoid unnecessarily strict restrictions on output power. Current exposure limits for the terahertz frequency band fall under both laser safety standards (0.3 THz to 10 THz) and radiofrequency radiation safety standards (0.1 THz to 0.3 THz). These standards are the ANSI Z136.1 American National Standard for Safe Use of Lasers (American National Standards Institute 2000) and the International Electrotechnical Commission (IEC) 80625-1 Standard (International Electrotechnical Commission IEC 2001) for laser exposures and the IEEE C95.1 Standard (Institute of Electrical and Electronics Engineers 2005) for radiofrequency exposures.

The use of both types of these standards leads to a number of complications. The first is that the two standards are defined very differently. Laser standards are defined by Maximum Permissible Exposures (MPEs) which are typically expressed as irradiance (W cm^{-2}) or radiant exposure (J cm^{-2}). Radiofrequency exposure limits or Permissible Exposure Limits (PELs) are generally expressed as maximal specific absorption rate (SAR), in units of W kg^{-1}. In addition to the difference in definition and units, the exposure limits represent two distinct endpoints. For the laser standard, the threshold is tissue damage while for the radiofrequency standard, the endpoint is psychophysical perception. To date, no empirical studies have been performed to test either of these thresholds. Currently, the standards within the terahertz region are based on extrapolation of empirical data from each side of the spectrum. Empirical data is necessary to validate and/or reconcile the current safety standards.

To determine the interactions of terahertz energy with skin tissue, we first performed an analysis of the current theoretical methods used to determine the dielectric parameters of materials at all frequencies across the electromagnetic spectrum. Modeling work, using both optical and radiofrequency approaches, was also performed to understand how skin tissue might interact with terahertz energy. Finally, empirical research is being performed to measure experimental damage threshold values and, therefore, validate the models that have been developed. Following the establishment of the damage thresholds, the threshold for perception will also be studied. Cellular and molecular effects of both low and high-power terahertz emissions will be examined in the future as well.

2.0 METHODS

2.1 Modeling
Thermal modeling was performed to determine the damage threshold of skin tissue in the terahertz range of the electromagnetic spectrum. To do so, an approximate solution to the bio-heat equation (eqn 1) was computed. For this model, a two-dimensional, cylindrically symmetrical tissue construct was used. One of two different source terms was entered into the equation: the "optical model" source term or the "radiofrequency model" source term. The "optical model" source term is defined by eqn 2. This source term is estimated from a simple linear absorption commonly used for optical frequencies. The "radiofrequency model" source term is formulated through the use of FDTD, used to predict the SAR within single and multi-slab skin models. Once formulated, each source term was then entered into the bio-heat equation to predict thermal changes in the skin model. For this modeling, boundary conditions were also taken into account. Convective heat transfer, radiative heat loss, and evaporative heat loss were all addressed. Finally, the skin damage thresholds were predicted using a single rate-process model for damage. The activation energy and rate for tissue damage are measured experimentally for use in this model. The thermal response predicted in the bio-heat equation is linked to the thermal damage rate process and assigned a probability of causing tissue damage. The Arrhenius damage integral (eqn 3) is used to evaluate tissue damage. Damage threshold parameters consistent with models documented in the literature were selected for use in this process. Damage integral values approaching $\Omega = 1$ indicate irreversible thermal damage, commonly referred to as second-degree burns.

$$\rho c_p \frac{\partial v}{\partial t} = \frac{\kappa}{r}\frac{\partial v}{\partial r} + \frac{\partial}{\partial r}\left(\kappa\frac{\partial v}{\partial r}\right) + \frac{\partial}{\partial z}\left(\kappa\frac{\partial v}{\partial z}\right) + A + \bar{q} \qquad (1)$$

$$A(z,r,t) = h(z,r)H_o(\lambda,t)\mu_a(z,\lambda) \qquad (2)$$

$$\Omega(z,r) = C\int_{t_1}^{t_2}\exp\left(\frac{-E_a}{RT(t)}\right)dt \qquad (3)$$

2.2 Experiment

2.2.1 Facilities

To perform experiments on damage thresholds within the THz region of the spectrum, a source capable of producing sufficient power is required. Using the Free Electron Laser (FEL) facility, Jefferson Laboratory is capable of producing high-power (up to 100 kW peak power, 20 W average power) terahertz emissions. This is done by producing bunches of free electrons, which are brought to relativistic energies using an energy-recovering linac, and accelerated by a magnetic field to produce the THz emissions as synchrotron radiation[1]. The resultant emission is a broad-band, terahertz beam with a peak frequency of about 0.6 THz and detectable radiation up to several terahertz2. A collaboration with Jefferson Laboratory permitted access to the source for the following experiments.

2.2.2 Materials

Prior to a full animal study, we first performed a pilot study to characterize the Jefferson Laboratory terahertz emissions and determine the optimal parameters for the animal study. During the pilot study, we exposed 3 surrogates to terahertz emissions. The first surrogate was a chamois cloth, which is commonly used in laser damage threshold studies. A true chamois cloth is the skin of a chamois goat; however, the cloth used in this study was a synthetic material made to mimic the qualities of the chamois skin. The 1-mm thick chamois cloth was moistened for the exposures to mimic the high water content of skin. The cloth was kept slightly wet during the experiment by spraying it with a spray bottle. Three chamois cloths were used for the experiment.

The second material used was a laser phantom (LaserMan), created by scientists at AFRL/HEDO. The phantom is a mixture of a silicone rubber, albumin, and scattering and absorbing agents. These materials are mixed in varying amounts to create three distinct layers that optically mimic human skin, fat and muscle tissues. The foundation of the phantom is an epoxy resin mixture called Poly-Sil 73 (Poly-Tek Develop. Corp., PA). It is a silicone rubber often used in the creation of molds and casts. The Poly-Sil provides a stable material that is the same density as human tissue. It has very low absorbance and scattering properties, which allows for manipulation of these properties as desired through the use of additional materials. The epoxy was formed by mixing equal amounts of the resins called "A" and "B" into a 1-cm thick mold. Protein is added to act as a coagulation agent. The white color caused by the coagulation aids in visual determination of damage caused by exposure. The protein material used is an animal protein gel, SIM-TEST™ (Corbin, OR), which closely mimics the density of human muscle tissue. SIM-TEST™ is most often used as a ballistic medium in which studies are conducted on the effects of ammunition on human tissue. This material is approximately 10% protein and is very cost effective. India Ink (KOH-I-NOOR Inc., NJ) is also added to increase absorbance rates. The absorption properties of the ink act as a substitute for melanin; however, it has a spherical shape where melanin is ovoid. Finally, various colors (PolyColors, Polytek Develop. Corp., PA) can be added to achieve a realistic looking "skin" color.

The third material used was the terahertz phantom, TX 151, as described by Walker, et al[3]. TX151 (The Oil Research Centre, Lafayette, LA, USA) is a white powder that, when mixed with water, solidifies to a material with a rubber-like consistency. This material is reported to have similar absorption characteristics to human tissue within the terahertz range of frequencies. In this experiment, a TX 151 gel of 25% powder in distilled water was used to form a sample 1 cm thick.

2.2.3 Experimental Setup

A grid of 16 squares, (2.0 cm x 2.0 cm) was drawn on each material. The spot size on the material was 0.5 cm x 0.9 cm. Each square on chamois #1 was subject to a two-second exposure at irradiance levels ranging from 2.2 W cm^{-2} to 10.5 W cm^{-2}. Additional exposures of 5, 10 and 15 second durations were made on the remaining materials. Following each exposure, three graders rated the square on the grid as positive or negative for effect. A positive score was assigned to any square that at least 2 of the 3 graders rated as positive. All exposures were recorded with a Merlin MWIR Thermal Camera and thermal data was recorded with FLIR Systems ThermaCam Researcher Professional 2.8 SR-1 software. Maximum temperature and temperature rise of the material at the exposure site were later analyzed.

3.0 RESULTS

3.1 Theoretical

Pickwell, et al.[4] used the double-Debye formulation of the Debye process (eqn 4) to determine the complex permittivity of water, dermis and epidermis in the terahertz range. Equations for the optical properties (equations 5-8) of water, dermis and epidermis were derived in terms of the complex permittivity. The absorption coefficient (α) is related to the thermal relaxation time by eqn 9. The thermal relaxation time measures the time for the thermal energy to be dissipated, where kappa is the thermal diffusivity given by eqn 10. Table 1 shows the thermal properties of water, epidermis and dermis.

$$\hat{\varepsilon}(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_2}{1 + i\omega\tau_1} + \frac{\varepsilon_2 - \varepsilon_\infty}{1 + i\omega\tau_2} \tag{4}$$

$$n(\omega) = \left(\frac{\sqrt{\varepsilon'^2 + \varepsilon''^2} + \varepsilon'}{2} \right)^{\frac{1}{2}} \tag{5}$$

$$k(\omega) = \left(\frac{\sqrt{\varepsilon'^2 + \varepsilon''^2} - \varepsilon'}{2} \right)^{\frac{1}{2}} \tag{6}$$

$$\alpha(\omega) = \frac{2\omega}{c} \left(\frac{\sqrt{\varepsilon'^2 + \varepsilon''^2} - \varepsilon'}{2} \right)^{\frac{1}{2}} = \frac{2\omega}{c} k(\omega) \tag{7}$$

$$\sigma(\omega) = \varepsilon_0 \omega \left[\varepsilon''(\omega) \right] \tag{8}$$

$$\kappa = \frac{K}{\rho C} \tag{9}$$

$$\tau_{therm} = \frac{1}{4\kappa\alpha^2(\omega)} \tag{10}$$

	specific heat	Density	thermal conductivity	thermal diffusivity
Water	4.19	1	0.006	0.0015
Epidermis	2.24	1.21	0.002	0.0007
Dermis	3.66	1.06	0.005	0.0013

Table 1. Thermal properties of water, epidermis and dermis

3.2 Modeling

The initial modeling compared the central axial distribution of normalized SAR and linear absorption source terms for a two-layer skin model and uniform water slab for a 1 W cm^{-2}, 1 THz exposure. An

increased absorption at the epidermis-dermis interface is seen, as is an expected high surface absorption of energy. It is also noted that the two different source terms yield similar trends. The difference that exists is likely due to the incorporation of density in the SAR source term. The 2-D two-layer source terms from FDTD-SAR and linear absorption calculations were also compared. In this case, the beam was a Gaussian distributed, 1 cm (at e^{-1}), 1 W, 1 THz beam. Again, the two source terms were found to be similar. A contributing factor to the difference in this case is the fact that the radiofrequency source term includes reflections at the epidermis-dermis interface.

A damage threshold estimate was made, using either the FDTD-SAR or linear absorption source term, using the finite-difference heat-transfer model. Along with the damage threshold power value, an approximate damage depth and peak temperature rise at that depth were recorded. The estimated damage thresholds at 1 THz for both 1-D and 2-D (2 cm Gaussian beam) models were calculated. The damage threshold was calculated both in terms of irradiance (W cm^{-2}) and radiant exposure (J cm^{-2}). The effect of exposure duration (from ten microseconds to thirty seconds) on the estimated damage threshold was also measured. The calculated values were compared to the ANSI Z136.1-2000 standard at 0.3 THz. The calculated damage thresholds were found to be below the ANSI Z136.1-2000 standard values at 0.3 THz. Temperature rise at the damage threshold as a function of exposure time was computed both for a 1-D model as well as 2-D model using 0.03 cm and 2 cm beam diameters.

3.3 Experimental

Probit analysis was used to determine an ED 50 value of 7.14 W cm^{-2} for a two-second exposure on the chamois cloth. This correlates experimentally with a temperature rise of approximately 35-38 °C. The total energy absorbed at this exposure would be 8.6 Joules. Figure 1 shows change in temperature as a function of irradiance of the exposures of chamois #1.

A positive effect was recorded after only one of the exposures on the LaserMan phantom. This occurred after a 15 second exposure at an irradiance of 22.99 W cm^{-2}. The maximum temperature for this exposure was greater than the maximum temperature that the software can acquire (~124° C). The temperature rise was greater than the 88° C limit imposed by the software. No exposure resulted in a positive effect on the TX151 phantom.
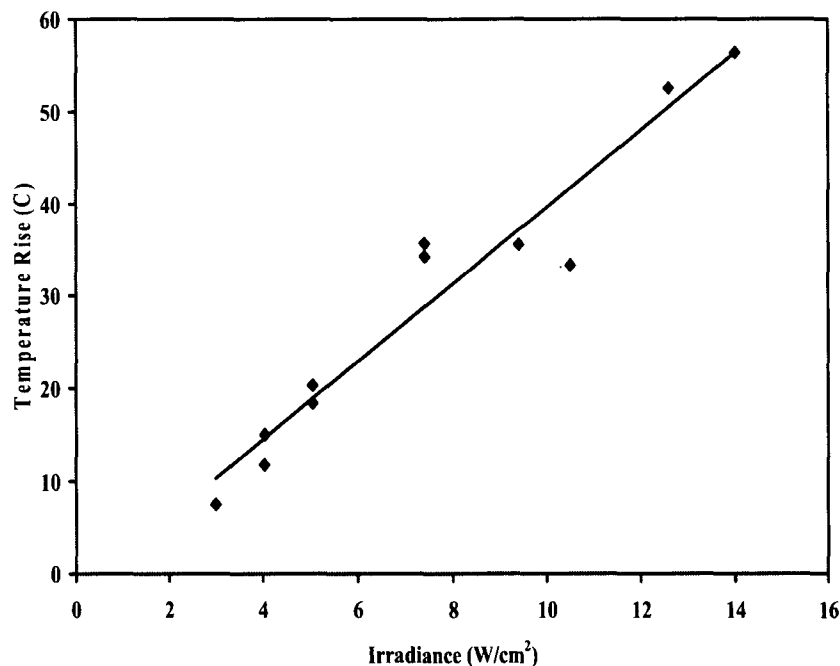
Fig 1. Temperature rise in degrees Celsius as a function of irradiance on a chamois cloth exposed to broadband terahertz energy.

4.0 CONCLUSIONS

As discussed in Yaws, et al in these proceedings, theoretical approaches in this region are quite complicated. Established models show mechanical excitation occurring from 300MHz-2GHz and electronic excitation in the far infrared and optical regions of the EM spectrum. However, these theoretical models are shown to not completely and accurately predict dielectric behavior in the terahertz range. Further theoretical work is necessary to incorporate both mechanical relaxation and electronic excitation into a comprehensive model that explains broadband, from 300MHz to optical, dielectric behavior.

The modeling effort has provided insight into tissue interaction with terahertz energy as well as initial estimates of the damage thresholds. Once further experimentation has been performed, the parameters from the experiments can be entered into the developed models for validation purposes. Due to the fact that the terahertz region of the spectrum spans regions covered by both laser safety standards and radiofrequency safety standards, any analysis must be compared to both of these standards. To fully understand the interaction of terahertz energy with tissue, both damage threshold as well as threshold to perception must be examined.

For a two-second exposure to a 2 cm, 1 THz beam, the modeling results show a second-degree burn damage threshold of approximately 4.5 W cm^{-2}. The experimental results revealed the ED 50 for a two-second exposure to a broadband, 0.605 cm^2 beam on a chamois cloth to be 7.14 W cm^{-2}. This is a fair agreement, especially considering the constraints of this initial experiment.

All experimental results acquired thus far are the result of a small pilot study. The purpose of this study was to determine if the modeling results could be validated through the use of a chamois cloth or the other phantom materials used. The pilot study was used to gain a general understanding of the Jefferson Laboratory facilities, the capabilities of the FEL to produce terahertz emissions, and the constraints that would be placed on our further experimental studies. The data gathered during this study was limited by a number of factors, including beam time availability during AFRL scientist's visit to the Jefferson Laboratory facility. Additionally, problems with the FLIR camera data recording did not permit full, accurate data records. A complete damage threshold study will be performed at Jefferson Laboratory in the future using a hairless guinea pig (HGP). The histology of the skin of the hairless guinea pig is considered to be similar to that of the human[5]. To ensure full understanding of the histology of the HGP skin, a histological analysis of the HGP skin will be performed prior to experiments at the Jefferson Laboratory. During the HGP study, plasma proteomics will also be performed to determine if any molecular changes can be detected in the guinea pig plasma following exposure to high-power terahertz energy.

Determining the damage thresholds within the terahertz region of the spectrum will permit comparison to the current laser safety standards. However, in order to examine the effects of terahertz emissions from the perspective of both lasers and radiofrequency radiation, perception thresholds must also be established. Therefore, following the experimental studies to determine the damage thresholds within the terahertz region of the spectrum, the perception thresholds will also be addressed. Additionally, cellular and molecular effects of both high and low-power terahertz emissions will be studied. The combination of this group of studies will lead to a thorough understanding of the effects of terahertz energy on biological tissue.

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